

## STUDY ON SEPARATION OF $^{137}\text{Cs}$ FROM $^{235}\text{U}$ FISSION PROCESS WASTE. UTILIZATION OF SILICA GEL-SUPPORTED FERROCYANIDE COMPLEX SALT FOR $^{137}\text{Cs}$ PICKING

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### ABSTRACT

**STUDY ON SEPARATION OF  $^{137}\text{Cs}$  FROM  $^{235}\text{U}$  FISSION PROCESS WASTE. UTILIZATION OF SILICA GEL-SUPPORTED FERROCYANIDE COMPLEX SALT FOR  $^{137}\text{Cs}$  PICKING.** In connection with the potential domestic demand especially in the fields of industry and nuclear medicine, the separation of  $^{137}\text{Cs}$  from  $^{235}\text{U}$  fission process waste is to be of interest although its economic value could be a polemic. A preliminary study on the separation of  $^{137}\text{Cs}$  from the  $^{235}\text{U}$  fission process waste generated in the production of  $^{99}\text{Mo}$  in P.T. BATAN Teknologi, Serpong, was performed through experiments on  $^{137}\text{Cs}$  picking from sample solution of the radioactive fission waste (RFW). The presented study is aimed to gain experimental data supporting utilization of the matrix of silica gel-supported ferrocyanide complex salt for the separation of  $^{137}\text{Cs}$  from RFW. Subsequent step would be the recovery and purification of  $^{137}\text{Cs}$  as part of production technology of  $^{137}\text{Cs}$ . The RFW sample was batch-treated with the matrix of silica gel-supported ferrocyanide complex salt which was synthesized from silica gel, potassium hexacyanoferrate(II) and copper(II) chloride. The binding of radioisotopes in RFW on the matrix was observed by  $\gamma$ -spectrometry of the RFW solution before and during the treatment. The results showed that approximately 85% of  $^{137}\text{Cs}$  could be picked from the RFW sample into the matrix. Less amount of  $^{95}\text{Zr}$  and  $^{95}\text{Nb}$  was bound into the matrix.  $^{103}\text{Ru}$  was slightly bound into the matrix whereas  $^{141/144}\text{Ce}$  and  $^{129\text{m}}\text{Te}$  were not. It was observed that by using 0.2 and 0.4 g of matrix for 10 ml of RFW, the amount of matrix influenced the binding quantity of  $^{95}\text{Zr}$  and  $^{95}\text{Nb}$  but not that of  $^{137}\text{Cs}$ .

FREE TERMS: Separation of  $^{137}\text{Cs}$ ,  $^{235}\text{U}$  fission process, Ferrocyanide complex salt, Radioactive fission waste (RFW),  $\gamma$ -spectrometry

### ABSTRAK

**STUDI PEMISAHAN  $^{137}\text{Cs}$  DARI LIMBAH PROSES FISI  $^{235}\text{U}$ . PENGGUNAAN MATRIK SILIKA GEL-GARAM KOMPLEK FEROSIANIDA UNTUK PEMUNGUTAN  $^{137}\text{Cs}$ .** Berkaitan dengan potensi kebutuhan domestik, terutama di bidang industri dan kedokteran nuklir, pemisahan  $^{137}\text{Cs}$  dari limbah proses fisi  $^{235}\text{U}$  menjadi hal yang menarik walaupun mungkin masih menjadi perdebatan apakah ekonomis atau tidak. Sebagai studi awal untuk pemisahan  $^{137}\text{Cs}$  dari limbah proses fisi  $^{235}\text{U}$ , telah dilakukan percobaan pemungutan  $^{137}\text{Cs}$  dari cuplikan limbah radioaktif proses fisi (radioactive fission waste, RFW) yang dihasilkan pada proses produksi  $^{99}\text{Mo}$  di P.T. BATAN Teknologi, Serpong. Percobaan ini bertujuan untuk mendapatkan data eksperimen yang mendukung penggunaan matrik silika gel-garam kompleks ferosianida untuk memisahkan  $^{137}\text{Cs}$  dari RFW. Tahapan selanjutnya adalah pemungutan dan pemurnian  $^{137}\text{Cs}$  sebagai bagian dari teknologi produksi  $^{137}\text{Cs}$ . Cuplikan RFW diperlakukan dalam proses batch dengan matrik silika gel-garam kompleks ferosianida yang dibuat dari silika gel, kalium heksasianoferat(II) dan tembaga(II) klorida.

*Pengikatan radioisotop dalam RFW pada matrik diamati dengan teknik spektrometri- $\gamma$  terhadap larutan RFW sebelum dan selama perlakuan dengan matrik. Hasil percobaan menunjukkan bahwa sekitar 85%  $^{137}\text{Cs}$  dapat terambil dari larutan RFW dan terikat pada matrik. Dalam kuantitas yang lebih rendah, radionuklida  $^{95}\text{Zr}$  dan  $^{95}\text{Nb}$  juga dapat terikat pada matrik. Radionuklida  $^{103}\text{Ru}$  terikat pada matrik dalam jumlah yang relatif kecil sedangkan radionuklida  $^{141/144}\text{Ce}$  dan  $^{129\text{m}}\text{Te}$  tidak terikat. Dengan menggunakan 0,2 dan 0,4 gram matrik untuk perlakuan terhadap 10 ml larutan RFW, dapat diamati adanya pengaruh jumlah matrik terhadap kuantisasi pengikatan  $^{95}\text{Zr}$  dan  $^{95}\text{Nb}$  tetapi tidak terhadap pengikatan  $^{137}\text{Cs}$ .*

**KATA KUNCI:** Pemisahan  $^{137}\text{Cs}$ , Proses fisi  $^{235}\text{U}$ , Garam kompleks ferosianida, Limbah radioaktif proses fisi (RFW), Spektrometri- $\gamma$

## I. INTRODUCTION

Cesium 137 ( $^{137}\text{Cs}$ ) is one of radioisotopes having multi-purpose utilization, especially in industry and medical fields<sup>[1]</sup>.  $^{137}\text{Cs}$  is not a natural radioisotope but can be obtained as a fission product of  $^{235}\text{U}$  with a fission yield of about 6%<sup>[2]</sup> meaning that about 6 atoms of  $^{137}\text{Cs}$  are produced in 100 fissions of  $^{235}\text{U}$ . The separation of  $^{137}\text{Cs}$  from fuel element waste is important due to the risk of increase of its temperature on decay being possible to give further risk on radiation safety<sup>[3]</sup>. By agreement, however, BATAN is not allowed to process the spent fuels. On the other side, radioisotope production process by  $^{235}\text{U}$  fission generates radioactive waste fraction containing various radioisotopes including  $^{137}\text{Cs}$ . Considering the potential domestic demand, the separation of  $^{137}\text{Cs}$  from  $^{235}\text{U}$  fission process waste is to be of interest, although its economic value could be a polemic.

P.T. BATAN Teknologi, a domestic government factory having activities related to commercial application of nuclear techniques, has routinely performed fission process of  $^{235}\text{U}$  to produce radioisotopes  $^{99}\text{Mo}$  and  $^{131}\text{I}$ . The process produces 4 fractions of fission products<sup>[4,5]</sup>, namely radioiodine fraction, radiomolybdenum fraction, radioxenon (noble gas) fraction and post-irradiated uranium fraction. The first two fission products are further processed to produce respectively  $^{131}\text{I}$  as  $\text{Na}^{131}\text{I}$  solution and  $^{99}\text{Mo}$  as  $\text{Na}_2^{99}\text{MoO}_4$  solution respectively. Meanwhile, the other two fission products are handled as radioactive waste in which the radioxenon fraction is kept in the gas form while the post-irradiated uranium fraction, which contains some other fission products besides the unfissioned uranium, including  $^{137}\text{Cs}$ , is kept in the concentrated-liquid form called radioactive fission waste (RFW).

The removal of  $^{137}\text{Cs}$  from the RFW can be performed by numerous methods based on solvent extraction<sup>[6,7]</sup>, adsorption<sup>[8]</sup>, ion exchange<sup>[9]</sup> as well as membrane techniques<sup>[10]</sup>. Most of the reported methods are not easily applied due to economic and technical problems such as complexity and high cost of the equipment especially for small-scale experiment, and rarity of the required chemicals that it is necessary to synthesize, which is neither a simple nor cheap process. On the other side, some ion exchange resins which are known to have specificity for cesium binding mostly have very fine particle size and need other supporting agent<sup>[11]</sup>.

As a preliminary study on the separation of  $^{137}\text{Cs}$  from the  $^{235}\text{U}$ -fission process waste, experiment on  $^{137}\text{Cs}$  picking from sample solution of the RFW generated from  $^{99}\text{Mo}$  production in P.T. BATAN Teknologi, Serpong, was performed. The sample of water-diluted RFW was batch-treated on a matrix of silica gel-supported ferrocyanide complex salt, which was

synthesized from silica gel, potassium hexacyanoferrate(II) and copper(II) chloride according to method for the determination of  $^{137}\text{Cs}$  in seawater reported by Chih Chieh Su et al.<sup>[12]</sup>. The use of silica gel-supported ferrocyanide complex salt is of interest as it can be prepared easily and was claimed to show satisfactory result in the pre-concentration and determination of cesium content in natural water<sup>[12,13]</sup>.

The presented study is aimed to gain experimental data supporting utilization of silica gel-supported ferrocyanide complex salt for the separation of  $^{137}\text{Cs}$  from RFW. Subsequent step would be the recovery and purification of  $^{137}\text{Cs}$  as part of production technology of  $^{137}\text{Cs}$  radioisotope.

## II. EXPERIMENTAL

### 2.1. Materials and Equipment

Sample solution of RFW from Radioisotope Production Laboratory, P.T. BATAN Teknologi, Serpong, was diluted with demineralized water to obtain lower radioactivities as necessary. The demineralized water was from water purification facility, Multi Purpose Reactor Center, BATAN. The main chemical materials were p.a. reagent grade, and from Merck, unless mentioned otherwise, silica gel, copper(II) chloride and potassium hexacyanoferrate(II) trihydrates (p.a. Fluka).

The main equipment was  $\gamma$ -spectrometer with multi-channel analyzer Canberra 1000 complete with HP-Ge detector and software of MCA Genie 2000 VDM. The system was calibrated using point sources of  $^{57}\text{Co}$  (122 keV),  $^{137}\text{Cs}$  (661 keV) and  $^{60}\text{Co}$  (1332 keV) from Oxford Instruments Inc. (Gamma Source Set Model S-13). Magnetic stirrer plate from Thermoline Nouva was used for stirring and mixing. Eppendorf pipette of 5  $\mu\text{L}$  was used for sampling the solution to be measured.

### 2.2. Preparation of Matrix of Silica Gel-Supported Ferrocyanide Complex Salt

The matrix of silica gel-supported ferrocyanide complex salt was prepared according to method used by Chih Chieh Su et al.<sup>[12]</sup>. Approximately 5 g of silica gel was placed in a 250-ml beaker and mixed with 100 ml of 0.1 M potassium hexacyanoferrate(II) trihydrates, then stirred for about 1 hour. The mixture was then decanted or filtered. The solid product was dried in an oven at approximately 80 °C for about 24 hours.

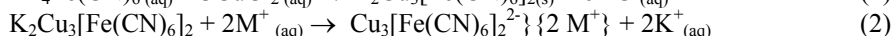
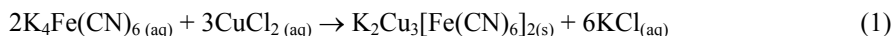
The dried matrix of silica gel-potassium hexacyanoferrate(II) was mixed with 100 ml of 0.2 M copper(II) chloride and stirred again for about 1 hour. The mixture was then decanted or filtered and the resulting solid product was water-washed and dried in an oven at about 80 °C for not less than 24 hours to obtain the matrix of ready-used silica gel-supported ferrocyanide complex salt.

### 2.3. Batch-Treatment of RFW Sample with the Matrix and $\gamma$ -spectrometry Analysis

10 ml of RFW sample was placed in a 100-ml beaker containing 0.2 g of the matrix. The mixture was combined and stirred at room temperature. With an interval of 1 hour each within 5 hours of stirring, the stirring was paused and the supernatant was cited carefully with 5- $\mu\text{L}$  Eppendorf pipette and sorbed on Whatman filter paper ( $d = 3.5$  cm). The filter paper was dried in air and then placed in a plastic purse specially provided for  $\gamma$ -spectrometry analysis. The samples were counted at a setting position for 600 sec. The results were compared to the count data from 5  $\mu\text{L}$  of initial RFW sample that was measured using separated filter paper. The experiment was repeated using an amount of 0.4 g of the matrix.

### III. RESULTS AND DISCUSSION

Some supporting or binding materials are required in preparation of resins having very fine particle size. It does not influence the ion exchanger behaviour of the resins but makes the resin more suitable for column preparation<sup>[11,13,14]</sup>. According to Chih Chieh Su<sup>[12]</sup> and Bellomo<sup>[15]</sup>, the ion exchanger behaviour of potassium hexacyanoferrate(II)-copper(II) chloride matrix is due to the formation of complex salt formulated as  $\text{K}_2\text{Cu}_3[\text{Fe}(\text{CN})_6]_2$ , which provides the  $\text{K}^+$  ions to be replaced by other cations. The chemical reaction of the matrix mixture and the ion exchange capabilities for monovalent cations ( $\text{M}^+$ ), for example, can be illustrated below:



The presence of silica gel in the matrix mixture is for supporting material that binds the  $\text{K}_2\text{Cu}_3[\text{Fe}(\text{CN})_6]_2$  molecules to form coarser particles as stated by Terada et al.<sup>[13]</sup>. The mentioned function of the silica gel is comparable to the function of asbestos material in the matrix of zirconium phosphate-ammonium phosphotungstic acid complex inorganic ion exchanger as reported by Reddy et al.<sup>[14]</sup>.

The picking of radionuclides in the RFW by the matrix of silica gel-supported ferrocyanide complex salt can be observed by comparing the radionuclides and their radioactivity in the RFW before and after or during treatment with the matrix. It should be noted that in this study, it is restricted to  $\gamma$ -emitter radionuclides and  $\alpha$  or  $\beta$  emitters are ignored. The RFW sample used in this study was originally received from the Radioisotope Production Laboratory, P.T. BATAN Teknologi, Serpong as the post-irradiated uranium fraction generated by the process schemed in Figure1.

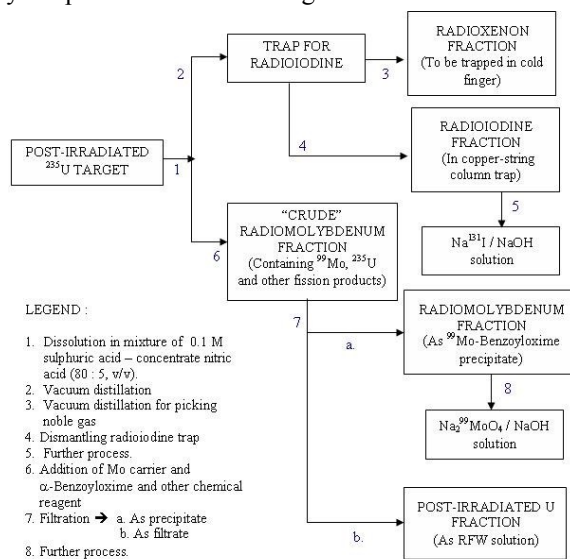


Figure 1. Scheme of process generating radioactive fission waste (RFW) (compiled from literatures<sup>[5,6,16,17]</sup>)

According to Figure 1, it is easily understood that there are numerous radionuclides other than  $^{137}\text{Cs}$  which can be found in RFW fraction. Nevertheless, some radionuclides could not be detected because the fission yields (Y) are too low, or the half-lives ( $T_{1/2}$ ) are too short. Some fission products were not detected by  $\gamma$ -spectrometry because they do not emit  $\gamma$ -rays. It can be seen in Table 1 that various radionuclides were significantly detected by  $\gamma$ -spectrometry of the RFW sample before being treated with the matrix of ferrocyanide complex salt. For each of the radionuclides, the count number on energy with highest intensity (I) was further used as calculation base for the fraction picked on the matrix.

Table 1. Typical resume of  $\gamma$ -spectrometry of RFW before being treated with the matrix of ferrocyanide complex salt

$E_\gamma$ (keV)	Radionuclide	Number of counts	Reference data <sup>[18]</sup>			
			$E_\gamma$ (keV)	I (%)	Y (%)	$T_{1/2}$ <sup>(a)</sup>
80.5	Ce-144	10788	80.1	1.6	5.47	284.6 d
133.6	Ce-144	124938	133.5	11.1		
145.8	Ce-141	21938	145.4	48.2	5.80	32.5 d
497.2	Ru-103	15390	497.1	90.9	3.04	39.27 d
610.5	Ru-103	720	610.3	5.6		
512.0	Ru-106 <sup>(b)</sup>	4180	511.9	20.4	0.403	1.02 y
622.5	Ru-106	1472	621.8	10.7		
1050.6	Ru-106	154	1050.5	1.7		
661.9	Cs-137	13208	661.7	85.2	6.22	30.17 y
696.8	Te-129m <sup>(c)</sup>	3502	695.9	3.3	0.127	33.6 d
			695.7	3.1		
724.5	Zr-95	48460	724.2	44.1	6.49	64 d
757.0	Zr-95	56563	756.7	54.5		
766.1	Nb-95 <sup>(d)</sup>	203537	765.8	99.8	6.49	34.97 d

Notes:

- d = days, y = years
- According to other references<sup>[19,20]</sup>  $^{106}\text{Ru}$  is a  $\beta$ -emitter emitting no  $\gamma$ -rays. The observing  $\gamma$ -rays are emitted by the daughter of  $^{106}\text{Ru}$ , i.e.  $^{106}\text{Rh}$ .
- The counts at 696.8 keV as stated from  $^{129\text{m}}\text{Te}$  probably overlap with the counts of activity at 697 keV springing from  $^{144}\text{Pr}$ , i.e. the daughter of  $^{144}\text{Ce}$  by  $\beta$ -decay.
- The counts of activity at 766.1 keV constitute accumulation of fission-produced  $^{95}\text{Nb}$  and  $^{95}\text{Nb}$  originated by  $\beta$ -decay of  $^{95}\text{Zr}$ .

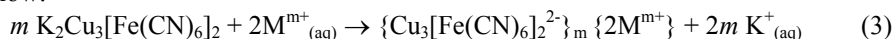
When the RFW solution was mixed and stirred with the matrix of silica gel-supported ferrocyanide complex salt, some radioisotopes appeared to be unbound on the matrix. This phenomenon was indicated by the fact that the count number of the cited RFW sample from the mixture at the concerning energy remained relatively unchanged as compared to that of

equivolume initial RFW sample. By treating 10 ml of RFW solution on 0.2 g of matrix, it can be seen from Figure 2(a) that neither radioactivity of  $^{144}\text{Ce}$  nor  $^{141}\text{Ce}$  in the solution decreased, indicating that cerium was not picked into the matrix.

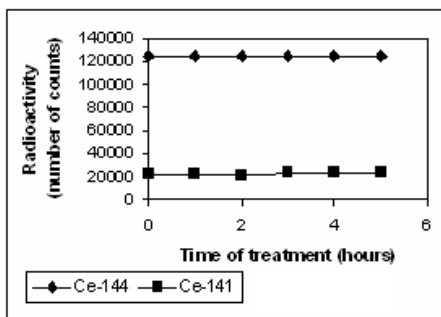
In the same system, it is shown in Figure 2(b) that like the cerium, tellurium is not picked into the matrix as indicated by the radioactivity of the  $^{129\text{m}}\text{Te}$  in the solution which remains relatively unchanged. On the contrary, the radioactivity of  $^{137}\text{Cs}$  in the RFW solution sharply dropped indicating that the cesium was bound and picked into the matrix. However, the capability of the matrix to bind radioisotopes from the RFW was observed not to be specific for cesium. It can be seen in Figure 2(c) that both  $^{95}\text{Zr}$  and  $^{95}\text{Nb}$  were significantly bound and picked into the matrix.

There was a slight difference in radioactivity profile between  $^{103}\text{Ru}$  and  $^{106}\text{Ru}$  which ought not to happen because the interaction between radioisotopes and the matrix is a chemical interaction. The observing data shown in Figure 2(d) indicates that the radioactivity of  $^{103}\text{Ru}$  represents the binding of ruthenium while that of  $^{106}\text{Ru}$  represents the binding of rhodium rather than ruthenium as  $^{106}\text{Ru}$  decays by  $\beta$ -ray emission to  $^{106}\text{Rh}$ , a non-fission product radioisotope emitting  $\gamma$ -rays of 511.9, 621.8 and 1050.5 keV (see notes below Table 1). Based on this reason, it can be stated that ruthenium was slightly bound on the matrix but not rhodium.

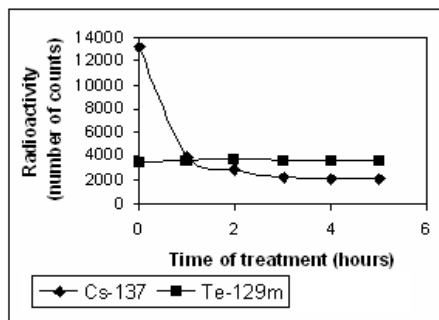
In order to see whether the quantity of binding would be affected by the amount of matrix, the RFW samples were treated with the matrix in the amounts of 0.2 and 0.4 g for a similar volume of RFW, i.e. 10 ml respectively. The reason to utilize such amounts of matrix is based on expectation that doubling the amount of matrix can give significant information whether the amount of matrix will affect the binding of radioisotopes or not. Meanwhile those amounts of matrix can be completely submerged in 10 ml of RFW solution. The evaluation was performed for cesium ( $^{137}\text{Cs}$ ), zirconium ( $^{95}\text{Zr}$ ) and niobium ( $^{95}\text{Nb}$ ) which were significantly bound on the matrix by means of cation exchange mechanism based on reaction (2), as follow:



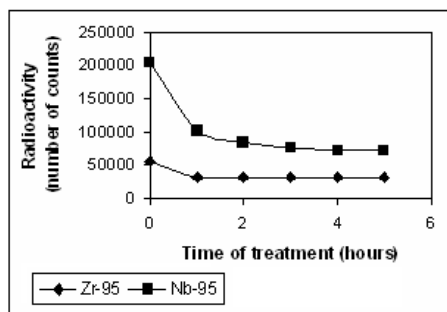
where  $\text{M}^{m+}$  represents ions of  $^{137}\text{Cs}$ ,  $^{95}\text{Zr}$  and  $^{95}\text{Nb}$  respectively.



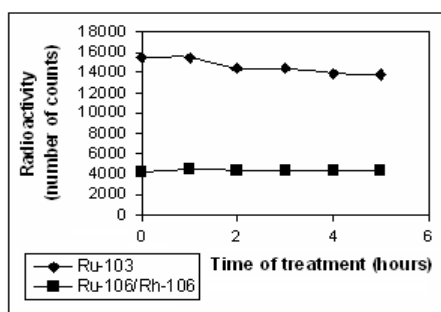
(a)



(b)



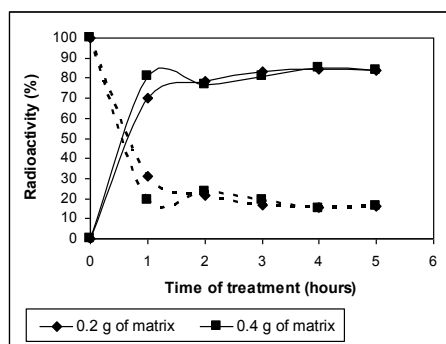
(c)



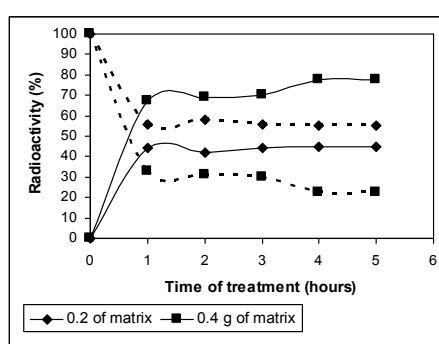
(d)

Figure 2. Radioactivity of some radionuclides in RFW sample before and during the treatment with 0.2 g of matrix

The results presented in Figure 3 show that the binding of  $^{137}\text{Cs}$  was not affected by the amount of the matrix, whether 0.2 or 0.4 g, but the binding quantity of  $^{95}\text{Zr}$  or  $^{95}\text{Nb}$  was significantly affected. The data indicates that the exchange between  $\text{K}^+$  in the solid matrix with  $\text{Cs}^+$  in RFW solution occurs more easily than with cations of zirconium and niobium which are usually in the forms of  $\text{Zr}^{4+}$  and  $\text{Nb}^{3+}$  or  $\text{Nb}^{5+}$ [21]. The  $\text{Cs}^+$  and  $\text{K}^+$  ions not only have similarity in charge but also they are members of the same group in the periodic table, so they resemble each other in chemical behaviour.



$^{137}\text{Cs}$



$^{95}\text{Zr}$

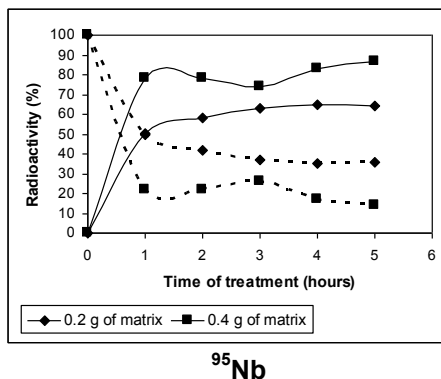


Figure 3. The influence of radioisotope binding on the amount of the matrix by using 10 ml of RFW solution (Dotted line: measured radioactivity remaining in the solution. Solid line: calculated radioactivity bound in the matrix)

In general, the equilibrium of radioisotope binding has been achieved in 2 hours of mixing and stirring the matrix with the RFW solution. Approximately 85% of the  $^{137}\text{Cs}$  was picked into the matrix, while the  $^{95}\text{Zr}$  and  $^{95}\text{Nb}$  were bound in the amount less than that of  $^{137}\text{Cs}$ . If the resulting data is further considered, a selective stripping method will be necessary to pick the  $^{137}\text{Cs}$  and thus to separate the  $^{137}\text{Cs}$  from  $^{95}\text{Zr}$  and  $^{95}\text{Nb}$ . Perhaps it can be performed by loading the matrix into a chromatographic column followed by elution with suitable solution in which the  $^{137}\text{Cs}^+$  will be eluted first before the other two. This experiment is now still in progress.

#### IV. CONCLUSIONS

The matrix synthesized from silica gel, potassium hexacyanoferrate(II) and copper(II) chloride was supposed to be a complex salt, i.e.  $\text{K}_2\text{Cu}_3[\text{Fe}(\text{CN})_6]_2$ , supported by silica gel to form coarser particles. The matrix shows capability to bind some  $^{235}\text{U}$  fission-produced radioisotopes from RFW solution.

The  $^{137}\text{Cs}$  from the RFW sample can be bound on the matrix in a quantity of about 85%, while the  $^{95}\text{Zr}$  and  $^{95}\text{Nb}$  was bound in an amount less than that of  $^{137}\text{Cs}$ . Radioisotope of ruthenium, represented by  $^{103}\text{Ru}$ , was slightly bound on the matrix, while  $^{144/141}\text{Ce}$  and  $^{129\text{m}}\text{Te}$  were not.

The amounts of 0.2 and 0.4 g of the matrix significantly affected the quantities of the  $^{95}\text{Zr}$  and  $^{95}\text{Nb}$  picked from the RFW into the matrix but not the  $^{137}\text{Cs}$ . As the capability of the matrix to bind radioisotopes is not specific for cesium, the picking of  $^{137}\text{Cs}$  from the matrix will need a specific stripping method to separate the  $^{137}\text{Cs}$  from other radioisotopes bound in the matrix.

#### V. ACKNOWLEDGEMENT

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## VI. REFERENCES

1. U.S. ENVIRONMENTAL PROTECTION AGENCY, “Radiation Information: Cesium”, <http://www.epa.gov/radiation/radionuclides/cesium.htm#whause>, March 2007.
2. ARGONNE NATIONAL LABORATORY, “Cesium”, Human Health Fact Sheet, August 2005, <http://www.ead.anl.gov/pub/doc/cesium.pdf>, March, 2007.
3. RIDDLE, C.L., “Fission Product Extraction Process. Removing Cesium and Strontium from Spent Nuclear Fuel”, INL Fact Sheet, <http://www.inl.gov/factsheets/rd100/fpex.pdf#search='fission%20product%20extraction%20process'>, February, 2006.
4. SOENARJO, S., GUNAWAN, A.H., PURWADI, B., and WISNUKATON, K., “Analysis of Radioiodine Fraction Separated from Production Process of Fission  $^{99}\text{Mo}$ ”, Atom Indonesia, Vol.25, No.2, 1999, pp.101-111.
5. ZAHIRUDDIN, “Produksi Radioisotop  $^{99}\text{Mo}$  dari Hasil Belah  $^{235}\text{U}$  dan Aspek Keselamatannya”, Prosiding Seminar Teknologi dan Keselamatan PLTN serta Fasilitas Nuklir, PPTKR – PRSG, BATAN, Serpong, 1993, hal.380-388.
6. LAW, J.D., HERBST, R.S., TODD, T.A., and WOOD, D.J., “Demonstration of a Universal Solvent Extraction Process for the Separation of Cesium and Strontium from Actual Acidic Tank Waste at the INEEL”, INEEL/CON-99-00092-Preprint, 1999.
7. WALKER, D.D., BEASLEY, M.H., COLEMAN, A.D., and CROY, B.H., “Solvent Extraction Batch Distribution Coefficients with Savannah River Site Dissolved Salt Cake”, WSRC-TR-2001-00533, Rev. 0, 2001.
8. DOE/EM-0575, “Innovative Technology Summary Report: Fission Products Separations Testing”, Document prepared for U.S. Department of Energy Office of Environmental Management Office of Science and Technology, May, 2001.
9. PICKETT, J.B., AUSTIN, W.E., and DUKES, H.H., “Highly Selective Nuclide Removal from the R-Reactor Disassembly Basin at the SRS”, WM’02 Conference, Tucson, Arizona, February 24-29, 2002.
10. DOE/EM-0505, “Innovative Technology Summary Report: Empore<sup>TM</sup> Membrane Separation Technology”, Document prepared for U.S. Department of Energy Office of Environmental Management Office of Science and Technology, February, 2000.
11. YASSINE, T., “Stannic Silicomolybdate as Cesium Selective Cation Exchanger”, J. Radioanal. and Nucl. Chem., Articles, Vol.173, No.2, 1993, pp.387-393.
12. SU, C.C, HUH, C.A., and CHEN, J.C., “A Rapid Method for the Determination of  $^{137}\text{Cs}$  in Seawater”, TAO, Vol.11, No. 4, 2000, pp.753-764.
13. TERADA, K., HAYAKAWA, H., SAWADA, K., and KIBA, T., “Silica Gel as Support for Inorganic Ion-Exchangers for the Determination of Caesium-137 in Natural Waters”, Talanta, 17, 1970, pp.955-963.
14. REDDY, V.N., SATYANARAYANA, J., and MARTY, G.S., “Studies on the Separation of Cs-137 from the Acidic Fission Product Waste Solutions on A New Complex Inorganic Exchanger (Zr-P-APW)”, J. Radioanal. and Nucl. Chem., Vol.183, No. 2, 1994, pp.371-377.
15. BELLOMO, A., “Formation of Copper(II), Zinc(II), Silver(I) and Lead(II) Ferrocyanides”, Talanta, Vol. 17, 1970, pp.1109-1114.
16. MEDI PHYSICS, “Manufacturing Manual of Fission Product Mo-99”, Document of Technology Transfer. (Unpublished document)
17. PUSAT PRODUKSI RADIOISOTOP, “Petunjuk Pelaksanaan Proses Pemisahan Mo-99 dari Hasil Belah U-235”, Dokumen internal No.RI-15-202-006. (Tidak dipublikasikan)

18. LIN, C.C., "Radiochemistry in Nuclear Power Reactors", The National Academy Press, Washington D.C., 1996.
19. CHU, S.Y.F., EKSTROM, L.P., and FIRESTONE, R.B., "The Lund/LBNL Nuclear Data Search", Version 2 1999, <http://nucleardata.nuclear.lu.se/nucleardata/toi/index.asp>, March, 2007.
20. EGGERBERT, W.S., PFENNIG, G., MUNZEL, H., and NEBENIUS, H.K., Karlsruher Nuklidkarte, Kernforschungszentrum Karlsruhe GmbH, 1981.
21. ANONYMOUS, "Periodic Table", <http://www.dayah.com/periodic/>, January, 2008.